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In this program we have succeeded in developing several photorefractive devices. We have a distortion compensating phase conjugate interferometer for the measurement of thin film thickness, refractive index and absorption coefficients. Also, we have investigated achromatic volume holography for adaptive optics applications. We have been working also on a device for passive mode locking of semiconductor lasers and have shown self pumped phase conjugation at 1.32μm, the longest wavelength to date at which self-pumped phase conjugation has been observed.

We have also made several theoretical advances. We now have an understanding of temporal instabilities in photorefractive phase conjugate mirrors. We are beginning to understand the effects of reduced spatial coherence in photorefractive devices, and using concepts developed in that work, we have analyzed our observations of high diffraction efficiency femtosecond two beam coupling in photorefractive crystals.

In the process of this research, one PhD and two masters degrees have been awarded, collaborations with seven other laboratories have been established, and a well equipped three table nonlinear optics lab with two argon lasers, a copper vapor

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Photorefractive Nonlinear Optics

Final Report

Mark Cronin-Golomb

January 15th 1991

US Army Research Office

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FOREWORD

The following constitutes the final report on a contract for a program of research into photorefractive nonlinear optics at the Electro-Optics Technology Center at Tufts University.

The strong optical nonlinearities associated with the photorefractive effect make possible high reflectivity phase conjugate mirrors, self-pumped phase conjugate mirrors and other oscillators that work with low power laser beams throughout the visible and into the near infrared.

In this program we have succeeded in developing several photorefractive devices. We have a distortion compensating phase conjugate interferometer for the measurement of thin film thickness, refractive index and absorption coefficients. Also, we have investigated achromatic volume holography for adaptive optics applications. We have been working also on a device for passive mode locking of semiconductor lasers and have shown self pumped phase conjugation at 1.32μm, the longest wavelength to date at which self-pumped phase conjugation has been observed.

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In the process of this research, one PhD and two masters degrees have been awarded, collaborations with seven other laboratories have been established, and a well equipped three table nonlinear optics lab with two argon lasers, a copper vapor laser, and a $Ti:Al_2O_3$ laser has been established at Tufts. We have one patent awarded, one patent pending, and seventeen publications.

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STATEMENT OF THE PROBLEM STUDIED

The problems studied in this research program were:
a) to understand temporal dynamics of photorefractive interactions,
b) to develop applications of the photorefractive effect and
c) to investigate the properties of several different photorefractive materials: indium phosphide, strontium barium niobate and lead germanate.

SUMMARY OF THE MOST IMPORTANT RESULTS

MATERIALS

Photorefractive Effect in Lead Germanate ($Pb_5Ge_3O_{11}$)

We observed a strong photorefractive effect in a sample of lead germanate from the Military Academy of Technology, Warsaw, Poland[1]. This crystal is a ferroelectric optically active crystal. Its highest electrooptic coefficient is 15pm/V, about three times more than that of $Bi_{12}SiO_{20}$ (BSO). Its optical activity, 8.67°/mm is about 25% of that of BSO, so that optical activity induced phase mismatch effects are much less severe than in BSO. The measured holographic diffraction efficiencies increased monotonically with decreasing grating periods, indicating that the trap density was very large by usual photorefractive standards. The maximum measured intensity gain coefficient was $2.3cm^{-1}$ at grating periods 0.14μm, corresponding to amplified backscattering at 515nm. If the background absorption in the crystal were not so high ($4.8cm^{-1}$), it might have been possible to observe phase conjugation by stimulated photorefractive backscattering. Also, we have observed some unusual temporal behaviors. One portion of the response has a very long time constant (several hours), which may find application in grating fixing for holographic memories. The component with short (about 500ms at 250mW/cm2) response time seems to be 180° out of phase with respect to the long period component, as evidenced by temporal oscillations in the diffraction efficiency (Fig. 1).

Strontium Barium Niobate

We entered into a collaboration with C.D. Brandle of AT&T Bell Labs to characterize and develop applications of photorefractive strontium barium niobate (SBN) that he has grown. His crystals were grown in an oxygen atmosphere and as grown did not exhibit strong photorefractivity. After reducing the crystals by annealing them in air, we found very strong photorefractive effects with good time constants (600 ms at $1W/cm^2$ illumination).

Diffraction imaging of photorefractive crystals with synchrotron radiation.

One of the main problems to be overcome for practical applications of photorefractive crystals in optical information processing is the large amount of light scattering due to imperfections in crystals. For example, laser beams are easily visible as they pass through most crystals of barium titanate. This indicates that there are many scattering centers in the crystal. These scattering centers are what makes the photographs of beams in self-pumped phase conjugators possible. Because of the photorefractive gain is so large, this scattering is amplified many times and is probably responsible for the so-called "fanning effect" in which a broad fan of amplified scattered radiation builds up. The fanning is a source of noise, and must be reduced if reliable, high signal to noise optical computers are to be built.

With this in mind we started a collaboration with Bruce Steiner of the National Institute of Standards and Technology in which we are performing diffractive imaging of photorefractive crystals using the bright monochromatic X-rays available at the National Synchrotron Light Source at Brookhaven. In this work, which is now separately funded, we will correlate the X-ray diffraction image findings to photorefractive optical measurements. We have already performed some experiments on barium titanate from Sanders Associates and Hughes Research Labs, and on potassium niobate from Virgo Optics. So far, uneven polishing has prevented us from seeing internal structure in any great detail. We also plan to image the crystal stresses associated with photorefractive gratings.

TEMPORAL STABILITY OF FOUR WAVE MIXING IN PHOTOREFRACTIVE CRYSTALS

The nonlinear steady state theory of phase conjugation in photorefractive crystals indicates multiple solutions in reflectivity for phase conjugate mirrors with typical crystals of barium titanate ($\gamma \ell \approx -3$ where ℓ is the crystal length). Multiple solutions in a nonlinear optical device often indicate bistability, and bistability is a key ingredient for the development of memory in optical computers. The extensive research in self-electro-optic-devices (SEED's) and bistable nonlinear Fabry Perot etalons is driven in large part by that the optical memory application.

But the existence of multiple solutions by itself does not guarantee bistability: The states corresponding to at least two of these solutions must be stable in time. That is, if a system is placed in a state corresponding to one of the memory levels, it must remain there and return there even when a small perturbation (unavoidable in the real world) is applied. An analysis of the stability of the various levels requires solution of the time dependent equations of the system so that the response to small perturbations can be investigated. We performed these investigations[2][3] using two complementary approaches. The first was a linear stability analysis, and the second was direct numerical integration of the coupled wave equations. Using our newly developed theory, we were able to show that externally pumped phase conjugate mirrors hardly ever have more than one stable state, and that for high coupling constants, all of the solutions can become unstable. However self-pumped phase conjugate mirrors such as the semilinear mirror can easily be bistable[4].

A natural follow on was to inquire about the nature of the instabilities. The simplest instability is a simple monotonic transition from the initial unstable state to a stable state. The next possibility is for the transition to have oscillatory (pulsating) components. Another possibility is the development of a persistent temporal oscillation. With variation of system parameters, this oscillation can experience a transition, perhaps through period doubling, to chaos. We found that all of these scenarios were possible in externally pumped phase conjugate mirrors[5].

Stability in externally pumped phase conjugate mirrors

In the initial stages of this work, we studied the behavior of externally pumped phase conjugate mirrors. The most important results were:

a) Bistability was possible only for a very limited range of probe ratios (ratio of signal beam intensity to total pumping beam intensity)

b) For sufficiently high coupling constants ($\gamma\ell > 2\pi$), it is possible to find system parameters (input intensities) where there is no stable state at all. The phase conjugate mirror will always experience temporal oscillations.

c) Some solutions are "conditionally stable". These solutions are stable for intensity perturbations with fixed phase, but are unstable for phase perturbations. Since almost all actual perturbations in any experiment will have a phase component, the conditionally stable solutions will almost always be actually unstable.

d) The occurrence of chaos requires that at least two conditions be satisfied: the coupling constant of the system must be above the self-oscillation threshold and the coupling constant must be complex. For this to occur in diffusion dominated[1] crystals such as barium titanate, it is necessary to apply an external electric field. The reasons for these requirements may be understood in term of the two different sources for a phase conjugate signal in such a phase conjugate mirror. We consider the positive feedback case of orthogonally polarized pumping beams in cubic crystals [6]. Firstly, a phase conjugate signal is induced directly by the incident probe beam. In the case of degenerate four-wave mixing considered here, the phase conjugate beam should have the same frequency as the probe beam. Secondly, there is the self-oscillation signal: the signal that would be induced even in the absence of a probe beam. In diffusion dominated crystals with applied electric field, the frequency of the self oscillation beam differs from that of the pumping beams. It is the beating between the first and second sources of the phase conjugate beam that gives rise to the observed pulsations and chaos.

e) An experiment[7] using barium titanate showed probable chaotic behavior, as evidenced by the fractal dimension of its strange attractor measured at 5.7 by the embedding technique of Grassberger and Procaccia[8]. The results were very sensitive to alignment of the pumping beams, as was explained using the theory of Goltz et al.[9] and Denz et al.[10] for four wave mixing with slightly misaligned pumping beams. It turns out that such misalignment can substantially enhance the phase conjugate reflectivity and alter its temporal dynamics.

Stability in self-pumped phase conjugate mirrors

The methods reported in the previous section were also used to analyze self-pumped phase conjugate mirrors.

We performed experiments using strontium barium niobate in the ring mirror configuration with external seeding (Fig. 2) to test theoretical predictions of temporal instability induced by electric fields applied to the crystal[11]. These experiments followed on from the work on instabilities in externally pumped phase conjugate mirrors described above. Again, we found that the alignment of the beams was critical, since even slight deviations from the Bragg condition had a large effect on the observed temporal oscillations.

It turns out that is much easier to find bistability in the self-pumped phase conjugate mirrors such as the semi-linear mirror (Fig. 3). The bistability in the phase conjugate signal beam 4 is controlled by the intensity of switching beam 1. It might turn out

[1] In a diffusion dominated crystal, the charge carriers responsible for the photorefractive effect move by diffusion only, and not by drift (which could be induced, perhaps, by the photovoltaic effect).

to be possible to use this device as a pixelated image latch in an optical processor. The image to be stored could be encoded on beam 1, and read out on beams 2 and 3 even after the loading beam is turned off. To be used in this manner, the bistability should be made irreversible by *not* applying an electric field to the crystal. The record could be erased by flooding the crystal with background illumination.

DEVICES

Ring self-pumped phase conjugate mirror in InP:Fe at 1.32μm.

It has been known for some time that light at around 1.3μm can generate photorefractive gratings with very high diffraction efficiencies in InP:Fe. With that knowledge, we were able to collaborate with A. Glass at AT&T Bell Labs to demonstrate self-pumped phase conjugation at 1.32μm microns in photorefractive InP:Fe[12]. We achieved 11% reflectivity. This is the longest wavelength at which photorefractive self-pumped phase conjugation has been observed. The result may be very useful for applications at 1.3μm where optical fibers have very dispersion and low loss.

Total internal reflection ring self-pumped phase conjugate mirror.

The ring self-pumped phase conjugate mirror structure was inspired by the discovery and interpretation of the total internal reflection self pumped phase conjugate mirror (cat mirror) by Feinberg (Fig. 4). Since the double phase conjugate mirror in the cat mirror feedback loop can be considered as simply a loss element, we can imagine that removal of the double phase conjugate mirror would increase the reflectivity and lower the threshold of the device. The resulting device, the ring mirror was first demonstrated in 1983. The ring mirror required external feedback loops: it could not be realized in a total internal reflection device because crystals are usually cut with surfaces at 90° to each other. Reflection of the input beam at such perpendicular surfaces could not close the required feedback loop. To make a total internal reflection ring mirror, a crystal cut with surfaces at a slightly acute angle would be required. To test this idea, we cut a crystal of strontium barium niobate grown by C.D. Brandle of AT&T Bell Labs at the proper angles and found it would indeed exhibit total internal reflection ring self pumped phase conjugation[13].

Dynamically programmable optical interconnect

The double phase conjugate mirror shows some promise as a dynamically reprogrammable self-aligning optical interconnect. In the double phase conjugate mirror, two mutually incoherent beams, perhaps from separate semiconductor lasers on an integrated optics chip induce a hologram in a photorefractive crystal. This hologram diffracts light from the first source to the second source and vice versa, thereby establishing an interconnection between them. After the connection is established one of the lasers may be used as a transmitter to transmit temporally encoded information to a detector integrated into the second laser, or to that laser itself reverse biased as a detector. A generalized interconnection between several lasers and several detectors at various places in a computer may be recorded in the crystal by a sequential training process. Each single laser transmitter is turned on cyclically in turn, together with the lasers associated with its target detectors. The time averaged hologram forms the required interconnection with the proper fan out and fan in. The interconnection can be used for several seconds or minutes before it needs to be refreshed, if the transmitters are used at low power levels. We performed a demonstration of 2x2 interconnect using a chopper as the SLM and SBN as the photorefractive material[14]. We found interconnect efficiencies of 12% and 1% interchannel crosstalk. In a simple one to one connection, the lasers need not, and in fact should not be mutually coherent. A problem arises with this architecture in a connection with multiple targets. Light from mutually incoherent receiver lasers will tend wash out the grating. This effect is one aspect of the spatial coherence problem to be discussed below.

<u>Phase conjugate interferometric measurement of thin film optical parameters</u>

In 1975 Shamir and Graff[15] reported a method for determining the refractive index, absorption coefficient and thickness of thin films by using the film as a sample in an interferometer. While ellipsometry can only give two of the parameters in a single measurement, the interferometric method gives all three. However, difficulty in reliably aligning the device to obtain infinite spatial period fringes in the output made the method impractical. Optical distortions are to be expected in such a device, because one of the interferometer components is the sample itself, which may be on a distorting substrate.

We have developed and patented a phase conjugate Michelson interferometer that overcomes the alignment difficulty, and now have our first experimental results in which we characterized films of V_2O_5 and $LiCoO_2$ on a glass substrate[16][17]. Even with simple measurements from an oscilloscope, we were able to find the optical constants to 5% accuracy.

Currently, we are automating the process and investigating various methods for determining the optical parameters from the experimental measurements.

<u>Optical computing</u>

In collaboration with Professor R. Gonsalves of our Center, we investigated optical implementations of phase retrieval algorithms usually performed with digital computers. The Gershberg Saxton Algorithm is such a procedure. The idea is to record the intensity of an optical field using a conventional camera, and to restore the phase of the field by means of recursive Fourier Transforms and division of the field by its modulus. This division can be thought of as amplitude stripping. A complex field $Ae^{i\theta}$ goes to $e^{i\theta}$.

The Fourier Transforms and recursion can be done optically in parallel with optical resonators with (photorefractive) gain. The key to the implementation is the amplitude stripping. We investigated the use of gain saturation in photorefractive two-beam coupling for that purpose, and found that the with proper crystal alignment, the transfer function was indeed suitable for amplitude stripping. A typical transfer function is shown in Fig. 5. We checked interferometrically that the phase of the beam was preserved in the process[18].

The student working on that project is now a student fellow at Draper Labs, where she plans to investigate issues of accuracy and noise.

Semiconductor laser passive modelocking

We are continuing experiments to attempt passive mode locking of gallium arsenide semiconductor lasers using a phase conjugating external cavity. The cavity we will use is completed by the ring self-pumped phase conjugate mirror, which has been used successfully in the past in external cavity semiconductor lasers for linewidth narrowing, and tuning, and for coupling several semiconductor lasers together. We have chosen the ring mirror because it works with mode locked laser light, and there is a natural place in the cavity to insert a saturable absorber for colliding pulse mode locking. During the course of the experiment we have obtained saturable absorber quantum wells from GTE, and have had them ion bombarded and antireflection coated at MIT Lincoln Lab. The ion bombardment makes the exciton saturable absorption recovery time shorter than the laser gain recovery time. We have built a $Ti:Al_2O_3$ laser using a crystal donated by Lincoln Lab to characterize our quantum well samples. A high power semiconductor laser has been provided to us by Polaroid corporation. In the next month, we should have all of the pieces ready.

In the process of building the $Ti:Al_2O_3$ laser, we demonstrated a technique using phase conjugation to retroreflect and reuse the approximately 50% of the Argon laser pumping radiation not used in the first pass though the laser crystal. Using a total internal reflection self-pumped phase conjugator with 26% reflectivity, we were able to observe a 7% reduction on the laser threshold[19].

The question of just how short we can expect the pulses to be is treated in the section below describing experiments on femtosecond two beam coupling and phase conjugation.

Achromatic holography

In another line of experiments, we have been investigating a new method of for multifrequency real time volume holography[20]. The device is a form of grating interferometer that uses material dispersion in tilted recording media to compensate phase mismatch among the contributions to the hologram from the various frequencies in the received field. Applications include broad band phase conjugation, and nonlinear adaptive optics.

We performed an experimental study in which we measured the two-beam coupling diffraction efficiency as a function of grating tilt. The experimental data for writing with all lines argon laser light and for readout at 633nm HeNe and Rhodamine 6G dye laser light are shown in Fig. 6. They match quite well with the theory, which predicts an optimum angle for crystal tilt with respect to the writing beams.

We also demonstrated multifrequency self pumped phase conjugation in the double phase conjugate mirror. The fidelity of this conjugator is best when the crystal tilt is near the theoretical optimum.

We found that although we could write high diffraction efficiency holograms with temporally incoherent light, we could not use spatially incoherent white light. If the white light is not spatially coherent, then the fringe visibility will not be good over a large volume. By spatially filtering the white light to a suitable degree, It is possible to write gratings using white light after spatial filtering, but the resulting intensity of the writing beams is very low, so the response time of the crystal is very long.

EFFECTS OF SPATIAL COHERENCE ON PHOTOREFRACTIVE DEVICES

Our experience with white light and the achromatic holography device led us to explore the effects of spatial coherence in real time volume holography. The diffraction efficiency of a real time grating decreases as the spatial coherence of the writing beam decreases. This spatial coherence effect has great importance for several photorefractive devices. It reduces the effectiveness of the fanning optical limiter. It reduces the reflectivity of phase conjugate mirrors for laser light after modal scrambling in long lengths of fiber.

We have performed experiments and developed a theory to investigate the effects of reduced spatial coherence on photorefractive two beam coupling[21]. Although the present theory does not include the effect of diffraction from the photorefractive grating on spatial coherence, we find that we get a very good match between experiment and theory for sufficiently small coupling constants.

Light of reduced spatial coherence was produced by focussing argon laser light onto rotating ground glass. The degree of coherence could be found by varying the spot size on the glass. The resultant light was used in two different coupling geometries. In one geometry (Fig. 7a) the main effect of reducing coherence is to reduce the effective interaction length with no effect on the transverse gain distribution. In the other geometry (Fig 7b) the fringe visibility is reduced more towards the edge of the beams leading to a distortion of the transverse gain profile. Theoretical treatment of the second case requires the development of a two dimensional theory. Comparisons of experimental and theoretical predictions are shown in Fig. 8.

At the moment, we are developing a two dimensional theory of beam interactions with light of variable spatial coherence to examine the effect of the nonlinear interaction on the spatial coherence of the interacting beams.

FEMTOSECOND BEAM COUPLING IN PHOTOREFRACTIVE CRYSTALS

We have recently started research in collaboration with Professor J.G. Fujimoto at MIT on the nature of photorefractive coupling of ultrashort pulse mode locked laser light. This research continues the themes of our other research efforts on semiconductor laser mode locking and on spatial coherence effects.

In the experiments, we observed, pulse length preserving two-beam coupling of 40 femtosecond pulses from a colliding pulse mode locked laser. At first, it might be thought that since the pulses are only about 5μm long in the crystal and interfere only in a very narrow (about 100μm wide) slice of the crystal, the diffraction efficiency could not be very high. But it turns out that the Fresnel reflectivity from each of the grating fringes is high enough to compensate the fact that the number of grating periods is only twice the number of optical cycles in the interacting pulses.

It can be seen that the pulse width is approximately preserved in the interaction by considering the refractive index grating as a linear superposition of the gratings from each of the frequency components of the femtosecond pulses. Each of the frequency components of one beam is diffracted by its corresponding grating to give a reconstruction in which all components are phased to give a pulse with the original width.

The interaction region is shaped as shown in Fig. 9. Its height is $h=L_p/\sin\theta$ where L_p is the pulse length and θ is the half angle of intersection. For a 40 fs (12μm long pulse) with half angle 0.1

radian, $h = 120\mu m$. The grating period is $d = \lambda/(2\sin\theta)$ so that the number of grating fringes in that region is $h/d \approx 2L_p/\lambda$ which is twice the number of periods in the pulse. For a 40fs pulse at center wavelength $0.5\mu m$, that corresponds to 24 fringes.
The width h of interaction region is swept out through the length of the intersection region of the beams or the crystal length if that is less.

The fact that the beam meets only a small number of grating planes is compensated by the largeness of Fresnel reflection coefficients at low angles of incidence θ. Simple geometrical considerations give the total number of fringes $N(\ell)$ traversed by the beam in travelling distance ℓ along the z axis. For simplicity, we assume that the coupling is weak, so that the fringe amplitude is approximately constant along the interaction length. The p polarization reflectivity from a grating stack $N(\ell)$ layers thick for small grating index amplitudes such that $2n\Delta n \ll \sin^2\theta$ is

$$R_s \approx \left[\frac{2\ell\Delta n}{\lambda\sqrt{1-\sin^2\theta/n^2}}\left(1-\frac{2\sin^2\theta}{n^2}\right)\right]^2$$

with a similar result holding for s polarization. This is the same as the diffraction efficiency of a photorefractive grating written by equal intensity continuous wave beams, as predicted by regular one dimensional coupled wave theory in the weak coupling limit. We thus have the result that even though the interaction is two dimensional, the diffraction efficiency can be predicted quite well from the simple one dimensional theory. The interaction length depends on the length of the crystal, not on the width of the interference region.

Self-pumped phase conjugate mirrors cannot be expected to perform as well as two beam coupling devices or externally pumped phase conjugate mirrors in short pulse applications. Referring to Fig. 10 of an externally pumped phase conjugator, we see that the location of the interaction slice is determined by the relative timing between beams 1 and 4. In the case of the double phase conjugate mirror, beam 1 is not externally supplied, but is induced as an oscillation beam. Its timing relative to beam 4 is not fixed, so the interaction slice can be anywhere (actually everywhere) in those parts of the beam overlap region where the interaction length is above threshold. The resultant hologram will act more like a volume hologram, with different frequency components of the interacting beams diffracted at different angles. The oscillation beams will undergo spatial dispersion, so that their temporal frequency spectra will vary and necessarily be narrowed across their cross sections. The diffracted pulses should be longer in the beam wings than in the beam centers. In the experiments in the ring mirror configuration, we saw that the oscillation beams were red on one side and orange on the other.

The fact that our discussion is in terms of the double phase conjugate mirror and the experiment was with the ring mirror makes no difference, since these devices are equivalent to each other.

EQUIVALENCE OF RING MIRROR TO DOUBLE PHASE CONJUGATE MIRROR

Using as a basis a phase conjugate mirror introduced by Zozulya and Mamaev involving two interconnected ring self-pumped phase conjugate mirrors, we have been able to show using topological manipulations that in the one dimensional theory the ring mirror is equivalent to a double phase conjugate mirror with twice the interaction length of the ring mirror (Fig 11). This result shows that all self-pumped phase conjugate mirrors, with the exception of the linear self-pumped phase conjugate mirror, are equivalent to each other[22].

LIST OF PUBLICATIONS AND TECHNICAL REPORTS

Submitted

"Effects of spatial coherence on photorefractive two beam coupling" H. Kong, C. Wu, and M. Cronin-Golomb submitted to Opt. Lett.

"Phase conjugate interferometric analysis of thin films", E. Parshall and M. Cronin-Golomb, submitted to Appl. Opt.

"Temporal instabilities in externally driven ring phase conjugator" W. Krolikowski, B.S. Chen, M. Cronin-Golomb, submitted to JOSA B

In Press

"Optical bistability in the semilinear phase conjugate mirror", W. Krolikowski, M. Cronin-Golomb, Appl. Phys. B (in press)

"Nonlinear optics and phase conjugation in photorefractive materials", M. Cronin-Golomb, Journ. Cryst. Growth

Published

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"Stability analysis and temporal behavior of four wave mixing in photorefractive crystals", W. Krolikowski, K.D. Shaw and M. Cronin-Golomb, J. Opt. Soc. Am. B6 1828 (1989).

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"Phase conjugate interferometric measurement of thin film parameters", M. Cronin-Golomb and J. Shamir, Appl. Opt. 28, 5196 (1989)

"Stability of multiple solutions in photorefractive four wave mixing with external electric field" K. Shaw and M. Cronin-Golomb, Opt. Commun. 76, 151 (1990)

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"Almost all photorefractive transmission grating self-pumped phase conjugate mirrors are equivalent", M. Cronin-Golomb, Opt. Lett. 15, 897 (1990)

Theses

"Optical information processing applications of two-beam coupling in photorefractive media", A.M. Biernacki, M.S. Thesis (Tufts University, Medford MA, 1990)

"Temporal behavior and nonlinear dynamics of photorefractive four-wave mixing" K.D Shaw, Ph.D. Thesis (Tufts University, Medford MA 1990)

"Phase conjugate interferometry for thin film analysis" E.R. Parshall M.S. Thesis (University of Arizona, Tuscon AZ 1990)

LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL SHOWING ANY ADVANCED DEGREES EARNED BY THEM WHILE EMPLOYED ON THE PROJECT

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A.M. Biernacki MS
K.D. Shaw PhD
G. Fogarty

REPORT OF INVENTIONS

"Phase conjugate interferometer for measuring thin film properties", M. Cronin-Golomb and J. Shamir, U.S. Patent #4,979,828

"Achromatic Holography Compensation", M Cronin-Golomb, Patent application number 531,623

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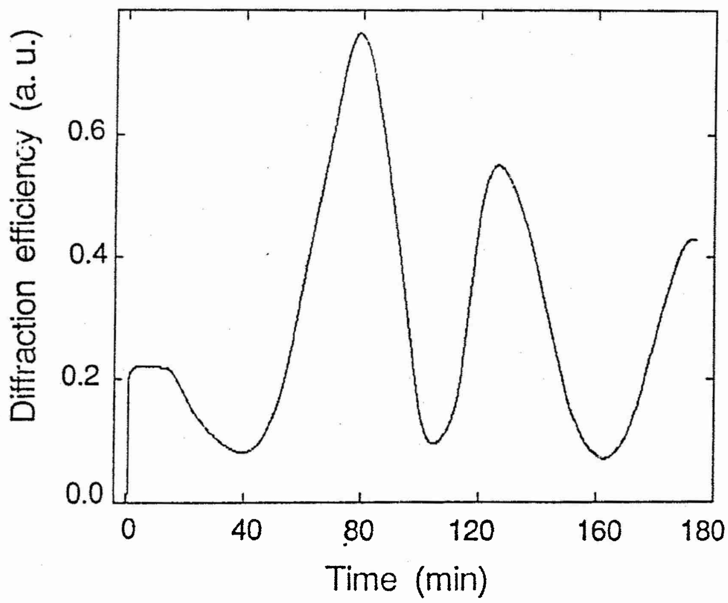


Figure 1. Time behavior of diffraction efficiency in $Pb_5Ge_3O_{11}$ in the case of long exposure (grating period 0.64μm, total light intensity 200mW/cm^2)

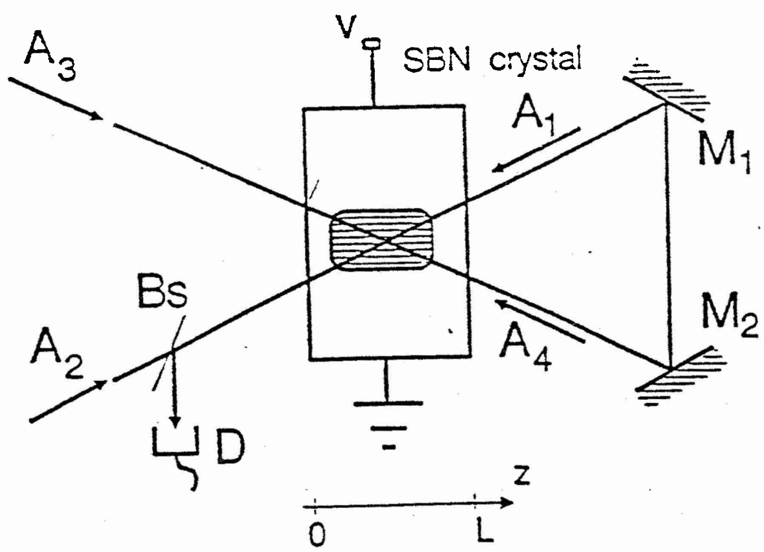


Figure 2. Experimental arrangement used to demonstrate instabilities in driven ring phase-conjugator. A_2 is a pump beam and A_3 is an injected signal beam; V is applied electric voltage.

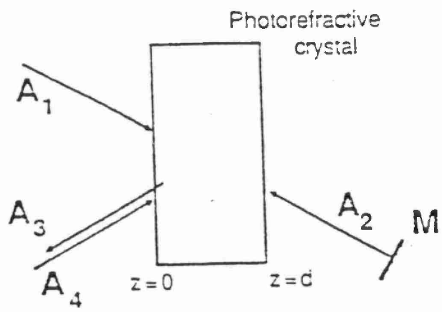


Figure 3. Geometry of bistable version of semilinear mirror. A_4 is the probe beam, A_1 is the input beam (seed), A_3 is the phase conjugate output.

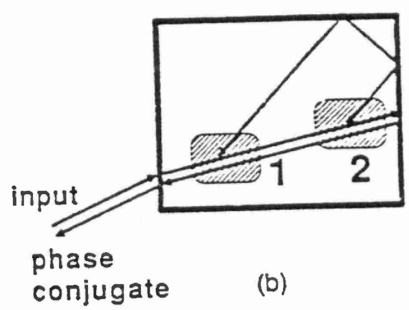


Figure 4. The rectangular total internal reflection self-pumped phase conjugate mirror (cat mirror). Region 1 is the ring mirror interaction region. Region 2 is the double phase conjugate mirror interaction region.

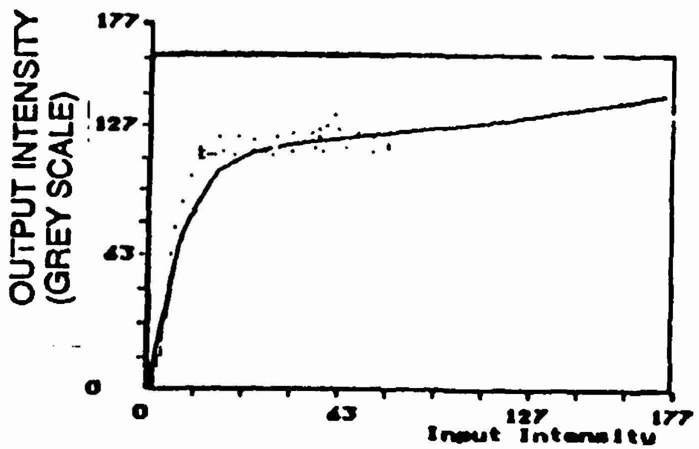


Figure 5 Saturated Gain: Gain Profile

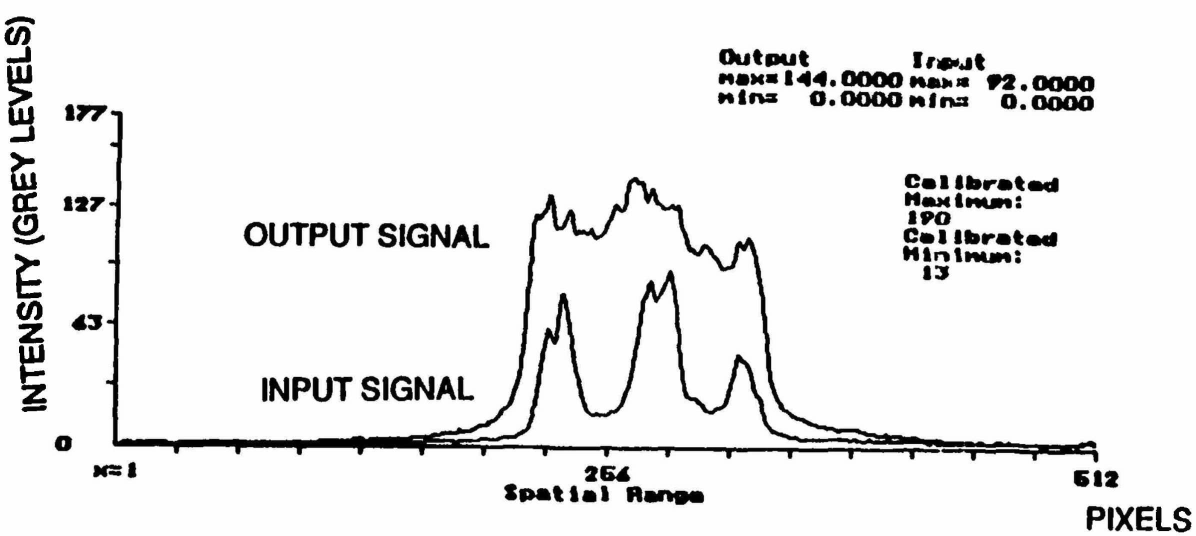


Figure 5 Saturated Gain: Single Line Scan Intensity Profile

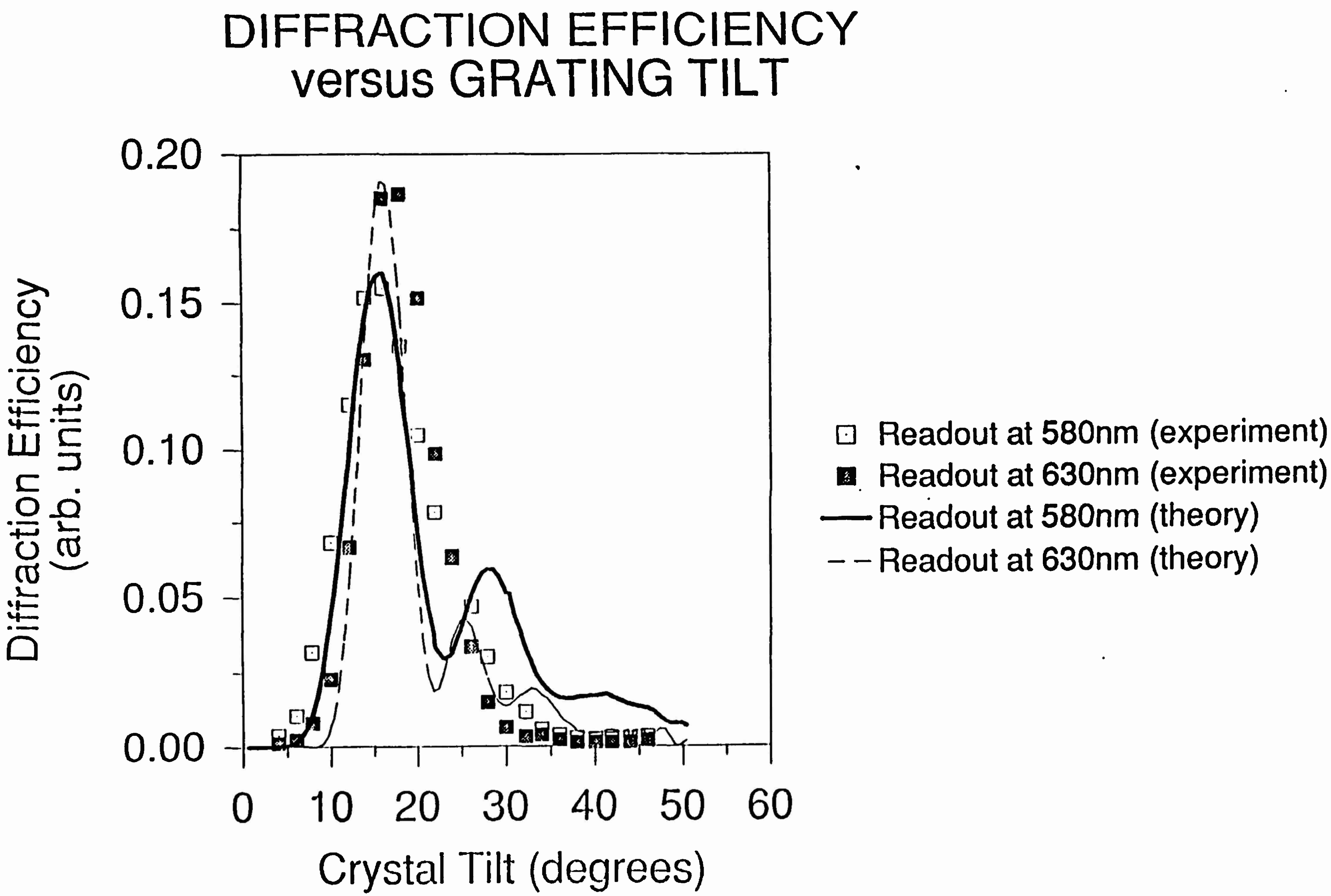
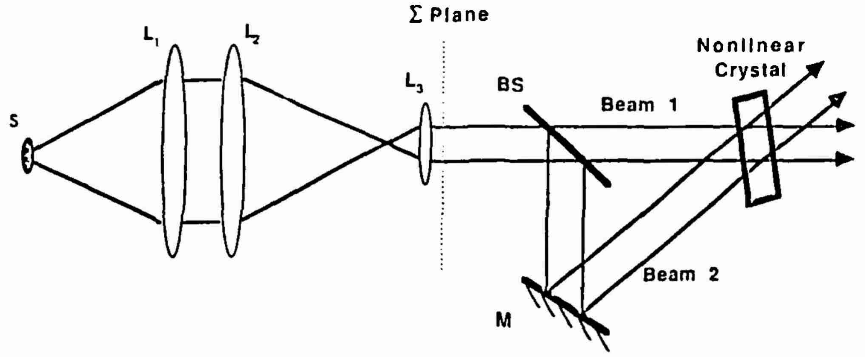
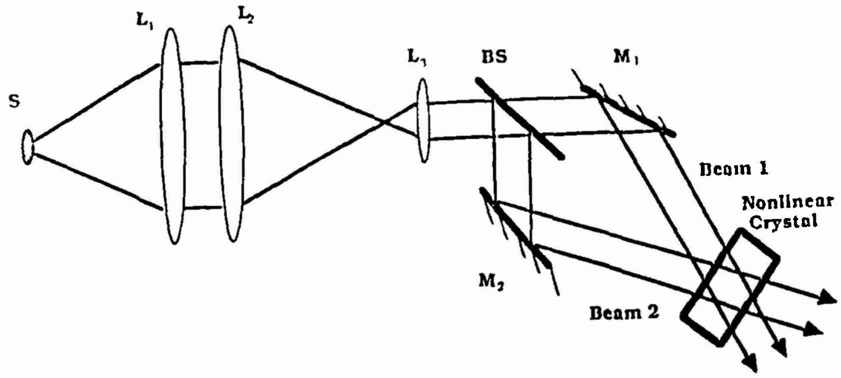


Figure 6. Diffraction efficiency versus crystal tilt for writing at all lines argon laser wavelengths and readout at 633nm HeNe and 580nm dye laser wavelengths in achromatic volume holography device.



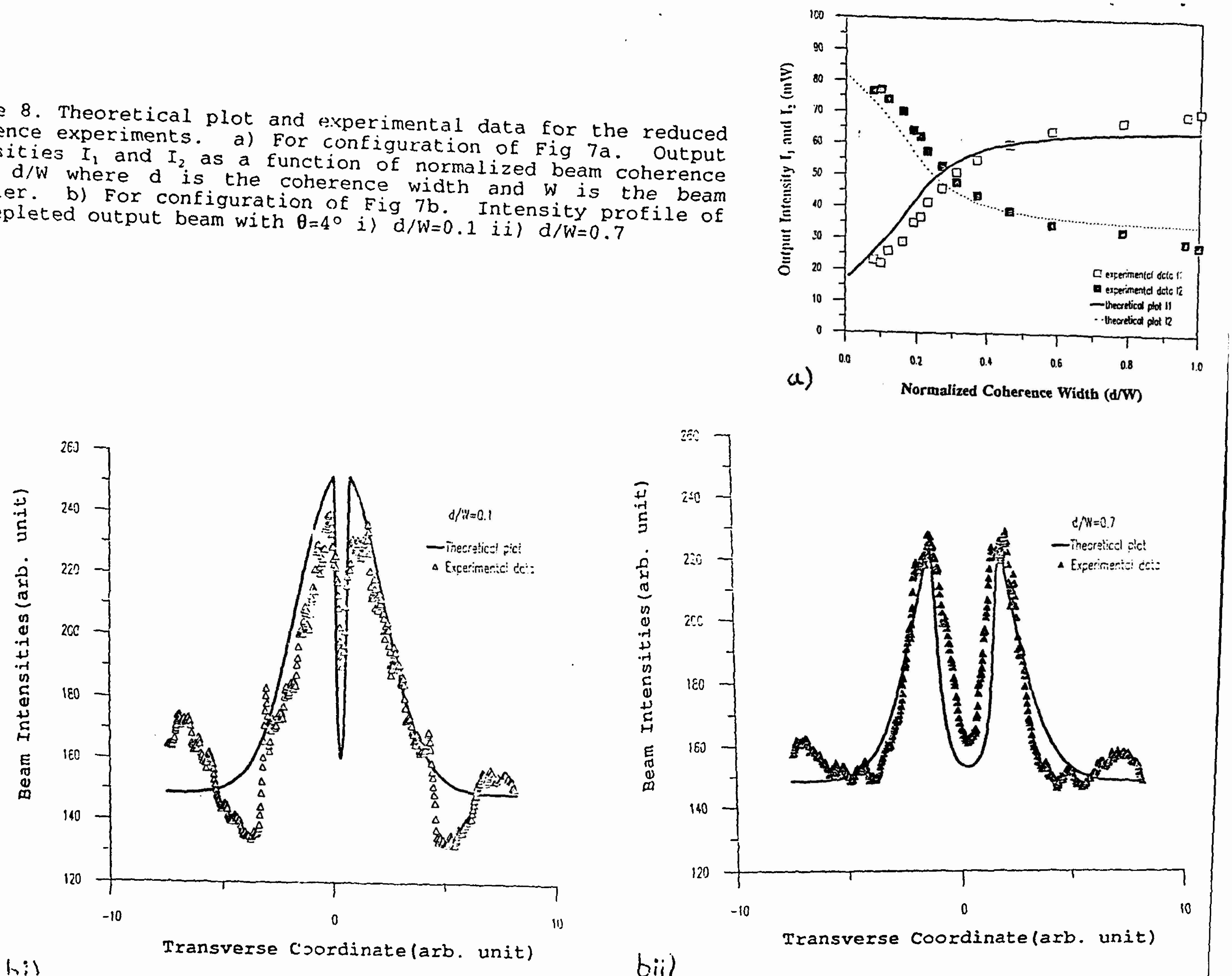
a)



b)

Figure 7. Schematic of two beam coupling configuration with reduced spatial coherence. S is an incoherent light source with circular symmetry.

Figure 8. Theoretical plot and experimental data for the reduced coherence experiments. a) For configuration of Fig 7a. Output intensities I_1 and I_2 as a function of normalized beam coherence width d/W where d is the coherence width and W is the beam diameter. b) For configuration of Fig 7b. Intensity profile of the depleted output beam with $\theta=4°$ i) d/W=0.1 ii) d/W=0.7



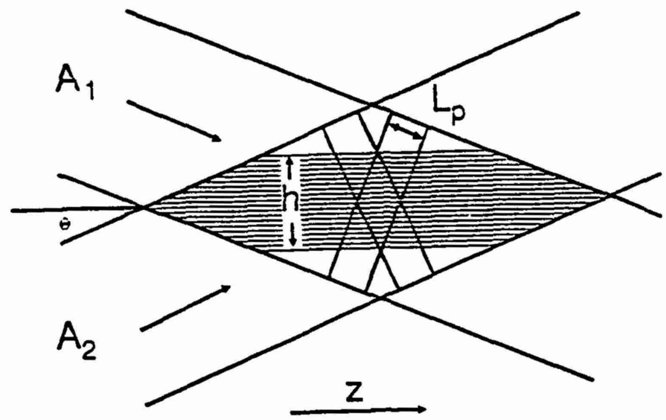
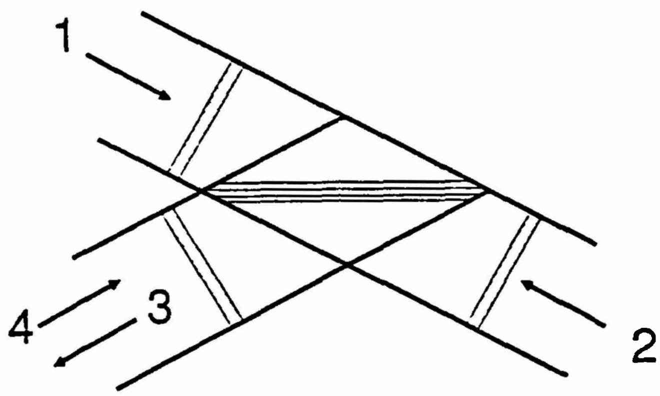
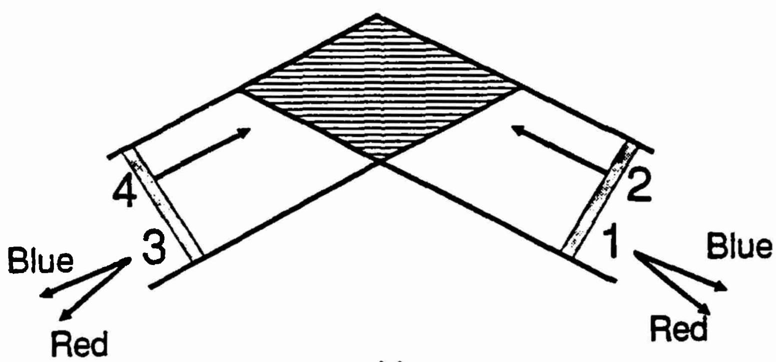


Figure 9. Beam interaction geometry for two beam coupling of two femtosecond mode-locked beams A_1 and A_2. L_p is the pulse length and h is the height of the interaction region.



a)



b)

Figure 10. Beam coupling geometry for a) externally pumped femtosecond phase conjugate mirror and b) femtosecond double phase conjugate mirror. In case b) the grating region covers most of the beam intersection, and the red components are diffracted at higher angles than the blue components

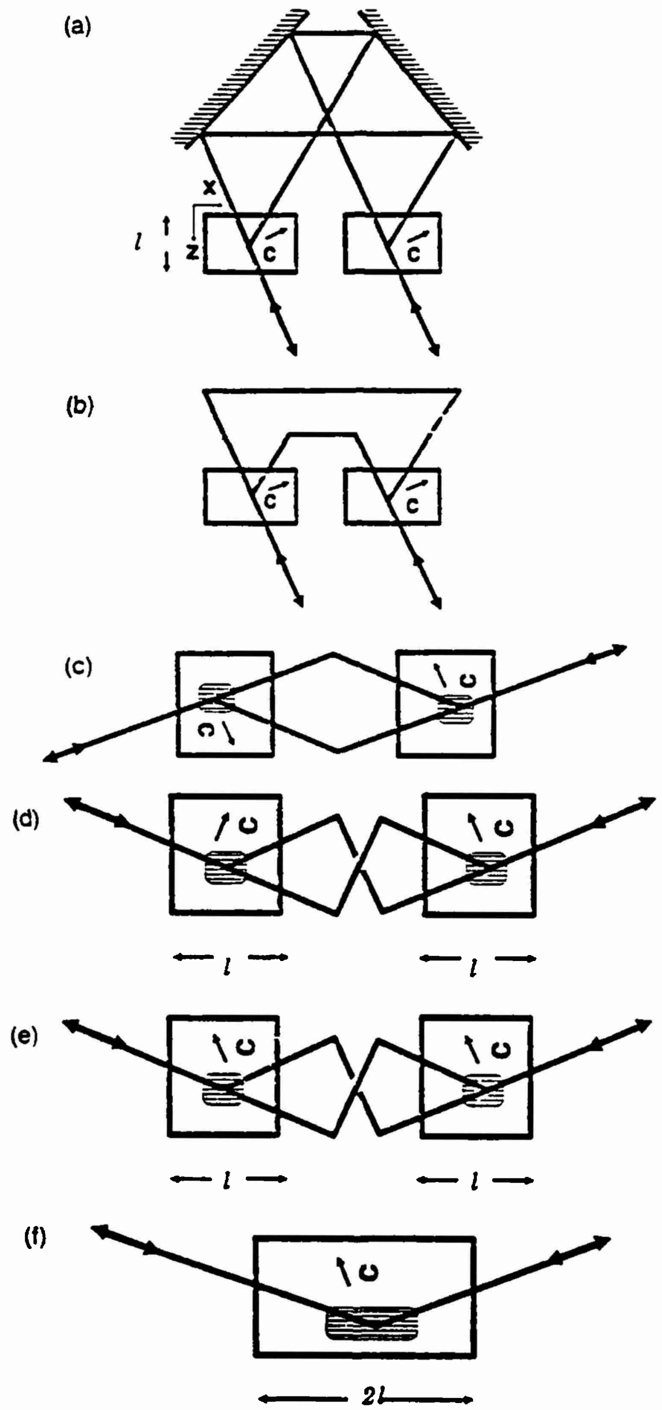


Fig. 11 Topological manipulations to demonstrate equivalence of the interconnected ring mirror to the DPCM. (a) Interconnected ring mirror, (b) topological equivalent, (c) interaction regions rotated by $\pi/2$, (d) left-hand interaction region and beams rotated by π about the horizontal axis, (e) left-hand interaction region rotated by π about the vertical axis, (f) interaction regions placed together to form a DPCM.